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NEUTRON-FLUX STUDIES IN THE EBWR DURING POWER OPERATION

by

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NEUTRON-FLUX STUDIES IN THE EBWR DURING POWER OPERATION

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Reactor Physics Division

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ABSTRACT

The neutron-flux distribution in the Experimental Boiling Water Reactor (EBWR) core during power operation has been studied through the use of activation foil detectors. The method described in ANL-7011 was used for irradiation and analysis of the detectors. From data obtained with bare and cadmium-covered, cobalt-aluminum alloy foils, neutron-flux isogram plots have been prepared. The effects of reactor power changes, soluble-poison concentration, and control rod positions on the thermal and resonance neutron-flux distribution are shown.

1. INTRODUCTION

The neutron-flux distribution in the EBWR core during power operation has been studied using a foil activation technique reported.[1] By this method, foils were introduced into specific core locations for short-term irradiation without affecting the normal reactor power operation. Bare and cadmium-covered cobalt foils were irradiated with selected reactor operating parameters. The effect of varying power, soluble poison concentrations, and control rod positions on the neutron flux distribution was determined. The data accumulated during the study and presented in this report will be of interest to reactor physicists and engineers concerned with neutronics of boiling-water reactors.

1.1 Objectives

The long-range objectives of the study were to characterize, as well as possible, both the neutron-flux distribution and the energy spectrum in the operating EBWR as a function of several operating parameters, namely power level, soluble-poison concentration, control rod positions, and fuel-loading configuration. These objectives were only partially realized during the time available for reactor experiments before the shutdown of the EBWR in December 1962. A firm ground work has been laid, however, for extension of the studies and a fuller realization of the objectives in future EBWR Plutonium Recycle Experiment cores.

The information obtained from these studies of neutron-flux distribution and, to a limited extent, of energy distribution in the EBWR, are useful for evaluation of fuel burnup, burnable poison effects, and radiation damage, and the determination of the most desirable conditions of reactor operation with respect to control parameters, i.e., control rod positions and soluble-poison concentration.

Since the application of specific neutron-flux data to a particular problem or area of interest is largely dependent on the parameters of the problem and the interests of the physicist or engineer making the study, it is proposed here to give as completely as possible the data and reactor parameters obtained, with a commentary on the data and the practical applications thereof. Application of the data to specific problems is left to the reader.

1.2 Background

Studies of neutron-flux distribution and energy spectra in reactors are the subject of many reports.(2-6) The techniques, methods, and modifications thereof well outnumber the reactors studied. Power reactors, however, have received a limited amount of study, primarily because of the difficulty of access for the neutron detection equipment. Previous studies have been almost entirely limited to the use of foil materials having sufficiently long-lived activation products to accommodate both a long irradiation time and a long postirradiation time to allow for removal and analysis of the detectors. Obviously, there could be little provision for extensive study of neutron distribution or energy as a function of various reactor parameters. The first indication of such an extensive study, using wires with provision for ready insertion and removal from the Vallecitos Boiling Water Reactor, was by Carver and Morgan.(2) Results of that study have not been published, but the selection of radioactivants proposed by those authors undoubtedly will be used in future studies on EBWR. With the method developed for fast insertion and removal of activation foils, and with the option of using cadmium covers, the door is opened for detailed study of power-reactor core neutronics, in spite of the high-pressure, high-temperature environment of the power-reactor core.

The EBWR is described briefly here; full details of the reactor design and operating parameters are available in the literature.(7-11)

The EBWR is a direct-cycle power reactor, with a heat dissipation capability of 100 MWt, as recently modified. It operates at 600 psi and 250°C (489°F). The reactor, in its 100-MWt design, was fueled with both plate and spike fuel assemblies. The plate-type assemblies were of doubly-enriched metallic uranium with Zircaloy-2 cladding. The spike assemblies were of highly-enriched uranium oxide pellets in Zircaloy tubing. Operational control was possible, both with the nine cruciform-shaped control rods, and with soluble poison (boric acid) dissolved in the coolant-moderator water. Fuel burnup compensation in the spike assemblies was provided by burnable poison (boron-stainless steel) strips affixed to the assemblies.

2. DETERMINATION OF NEUTRON-FLUX DISTRIBUTION IN EBWR

2.1 Method for Foil Irradiation and Analysis

The irradiation facilities, procedure, analytical method, and equipment are detailed in ANL-7011.[1]

The present study of the EBWR neutron-flux distribution was made by irradiating small, spherical (1/16-in. diameter), 1% cobalt-aluminum foils with and without 15-mil cadmium covers (see Fig. 1) in preselected locations in the core for 30 min. Using the technique previously mentioned, up to 60 such foils were simultaneously irradiated. The in-core locations for irradiation are shown in Fig. 2.

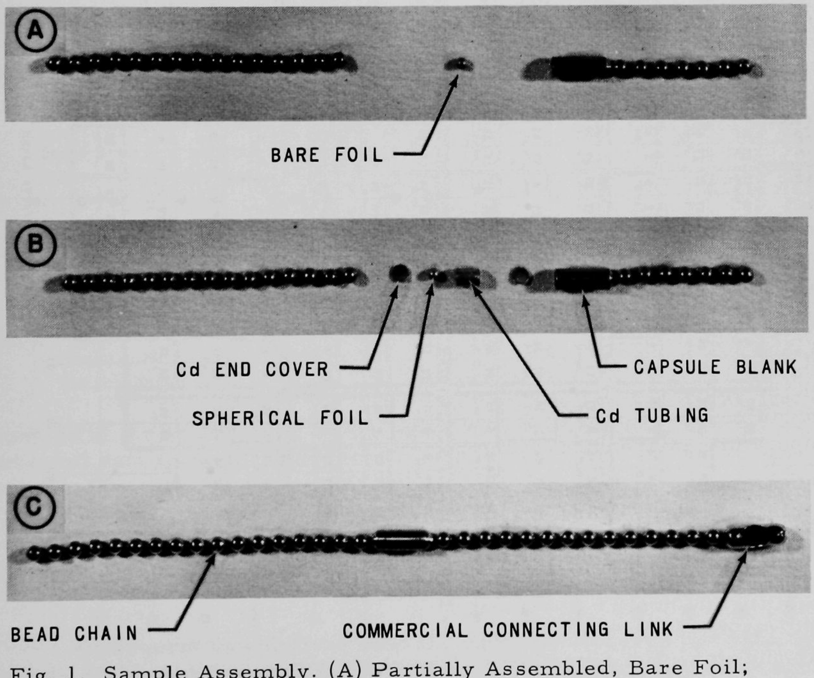

Fig. 1. Sample Assembly. (A) Partially Assembled, Bare Foil; (B) Partially Assembled, Cadmium-covered Foil; (C) Completed Assembly (Note Bead-chain Connector at Right End).

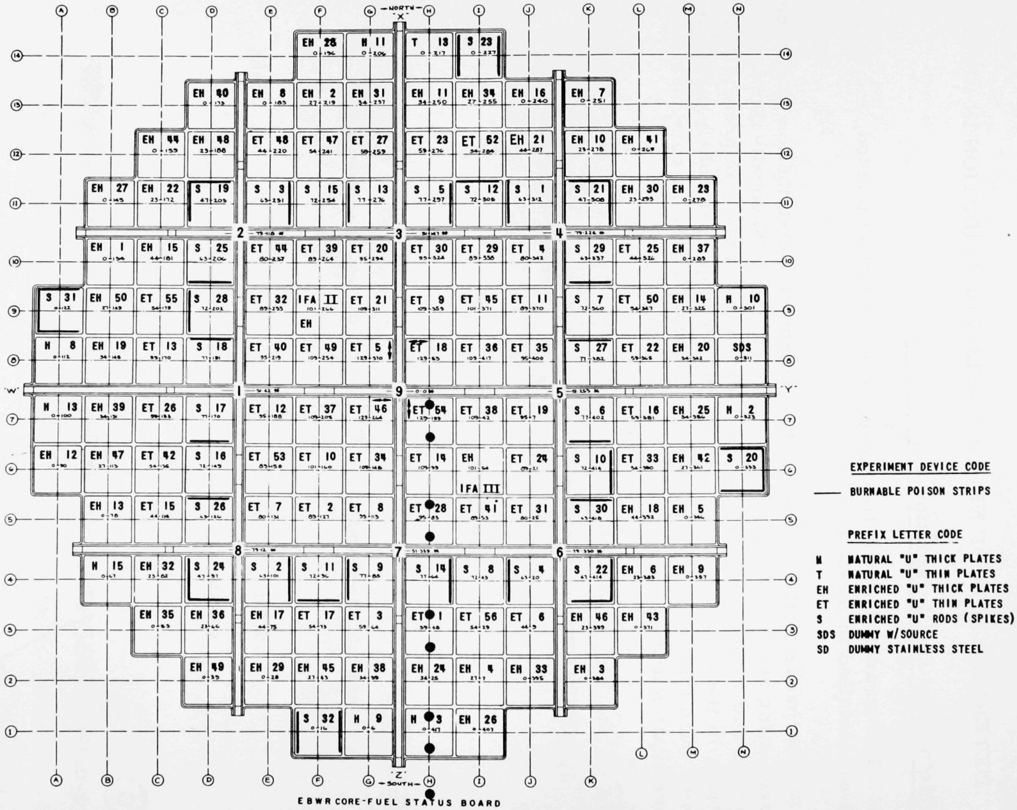

Fig. 2. Foil-irradiation Locations Used for Data Presented in Figs. 4-24, Inclusive.

The induced Co^{60} activity was measured with a NaI(Tl) scintillation detector and associated electronic equipment. Careful calibration of the detection equipment and the uniformity of the design and weight of the detector foils greatly simplified calculation of individual foil activities.

The cobalt concentration in the aluminum alloy was 1.01%. The average weight of the activation foils was 0.00571 g ±1%. The detection efficiency was determined from accurate radiochemical analysis of selected foils.

Figure 3 is a schematic diagram of the irradiation-analysis procedure.

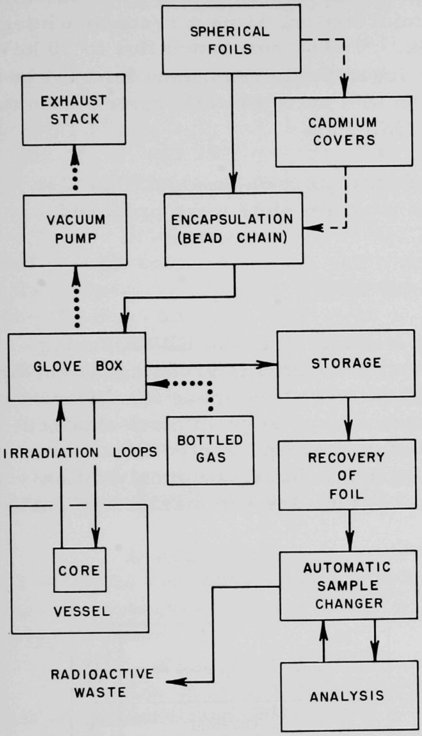

Fig. 3. Schematic Diagram of Irradiation-analysis Procedure Used in Study of EBWR Neutron-flux Distribution

2.2 Calculation of Neutron-flux Levels from Foil Data

In most cases, both bare and cadmium-covered foils were irradiated in identical core locations for a given set of reactor parameters. In a few cases, particularly where plant operating conditions limited personnel access to the reactor containment building, such as during high-power operation, it was possible to irradiate only bare samples. Because of the interest in these latter samples and the need for cross-comparison to similar samples irradiated at the other power levels, the first calculations used only the bare-foil data from all runs based on a σ of 36.0 b.[12] The resultant neutron-flux values for each foil were plotted, relative to the irradiation position of that foil within a given fuel assembly or in the reactor downcomer. From a series of these axial neutron-flux plots for a given reactor operating condition, a neutron-flux isogram plot was constructed, with levels of multiples and decimal multiples of 10^{13} n/(cm^2)(sec).

Subsequent calculations used the cadmium-covered foil data, giving thermal and resonance (dE/E) flux values. The thermal flux was calculated in the usual way, using σ equal to 26.0 b for the 250°C (489°F) reactor system [calculated according to Westcott[13]], where

$$\overline{\sigma} = \hat{\sigma}\sqrt{(\pi T_0/4T)}$$

The isogram plots of the thermal neutron-flux levels were calculated from bare and cadmium-covered foil information, using a resonance integral of 49.3 b for the total epicadmium flux.(14) The resonance flux to 50 keV was then obtained by integration of the logarithmic resonance interval between 0.4 eV and 50 keV. No correction was made for 1/V contribution to the activity of the cadmium-covered cobalt foils.

Each calculation gave an appropriate point on an axial-flux plot, from which the respective neutron-flux isogram plots were prepared.

3. DISCUSSION OF RESULTS

The data obtained by cobalt foil irradiation in the EBWR during power operation have been assembled and presented in groupings according to the operating power level. Subgroupings were then made for different soluble-poison concentrations. The neutron-flux isogram plots obtained with both bare and cadmium-covered foil data are presented first (see Figs. 4 to 13), and those derived from bare foil information only follow (see Figs. 14 to 24). The irradiation conditions are summarized in Table I.

Table I

SUMMARY OF IRRADIATION CONDITIONS FOR DATA IN FIGS. 4 TO 24, INCLUSIVE

Run No.	Power (MWt)	Rod Positions (in.)		H_3BO_3 Concentration (ppm)	Foils Activated		Calculated Flux	Fig. No.
		Nos. 1-8	No. 9		Co	Co-Cd		
1	21	22	22	25	X	X	Thermal Resonance (Bare Co Only)	4 5 14
2	41.2	26	26	25	X	X	Thermal Resonance (Bare Co Only)	6 7 15
3	40	48	43	900	X		(Bare Co Only)	16
4	42	48	44.5	1200	X	X	Thermal Resonance (Bare Co Only)	8 9 17
5	62	30.5	30.5	25	X	X	Thermal Resonance (Bare Co Only)	10 11 18
6	58	48	30	120	X	X	Thermal Resonance (Bare Co Only)	12 13 19
7	60	48	48	925	X		(Bare Co Only)	20
8	78-80	48	48	25	X		(Bare Co Only)	21
9	72	48	48	225	X		(Bare Co Only)	22
10	75	40.5	30	290	X		(Bare Co Only)	23
11	80	48	48	540	X		(Bare Co Only)	24

3.1 Effect of Reactor Power on Neutron-flux Distribution and Energy

3.1.1 In Absence of Soluble Poison

Considerable data were obtained at a variety of power levels where the concentration of soluble poison was at its lowest normal operating level and was practically insignificant (25 ppm). Power levels studied were ~20 MWt (Figs. 4, 5, and 14), ~40 MWt (Figs. 6, 7, and 15), ~60 MWt (Figs. 10, 11, and 18), and ~80 MWt (Fig. 21). Both bare and cadmium-covered foil data were available for all but the 80-MWt condition.

In the absence of soluble poison at powers up to 60 MWt, the control rods were inserted a significant distance into the core, as shown in the respective figures. This resulted in peak power production in the lower 12 in. of the fuel meat, with a rapid drop in power vertically through the core. The power peak is displaced from the core center, probably due to the effect of the central control rod. Whether the spike assembly ring contributes significantly to this displacement is subject to question. There is evidence that the vertical distribution of flux and, hence, power in the spike assemblies is more limited than in adjacent assemblies. This might be expected in the presence of the burnable poison strips attached to the spike assemblies.

A significant thermal-neutron reflux peak is observed at the bottom of the core, with flux levels approaching that of the peak-power zone. As expected, similar peaks are absent from the plots of higher-energy neutrons.

The peak flux of resonance neutrons is located at a higher point in the core than is the area of peak thermal neutron flux, with the control rods having a more observable effect on the radial distribution.

Operation of the 100-MWt EBWR core at powers of 60 MWt or less in absence of soluble poison resulted in an impractical (from a fuel economy point of view), pancake power distribution. Such a distribution could be of practical value, however, if the assemblies were designed to be inverted during a portion of their in-core life, as was initially proposed for EBWR Core II.[15]

The neutron flux incident upon the reactor vessel is not a linear function of the power level since the effect of raising the power level was primarily shown as increasing the height rather than the diameter of the effective core volumes.

3.1.2 In Presence of Soluble Poison

Irradiations were made at ~40 and ~60 MWt with very similar soluble-poison concentrations (~900 ppm), and at ~80 MWt with a somewhat

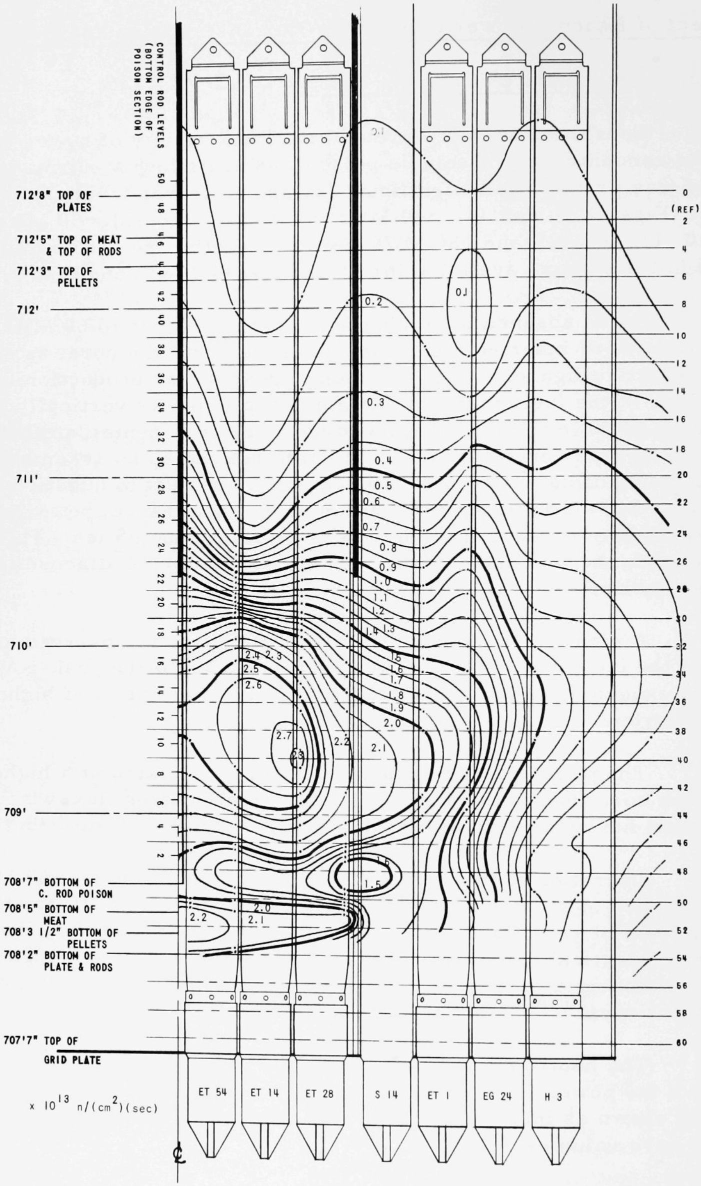

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Fig. 4. Thermal-neutron-flux Isogram Plot for Reactor Power of 21 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

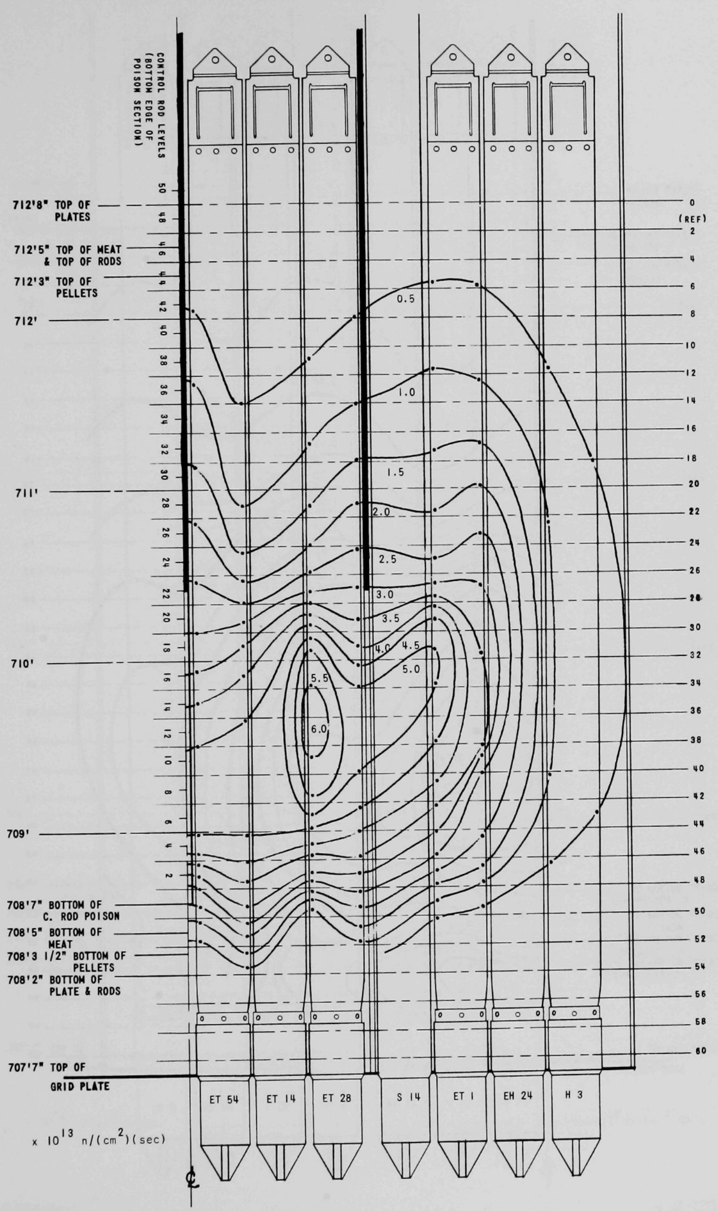

Fig. 5. Resonance-neutron-flux Isogram Plot for Reactor Power of 21 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

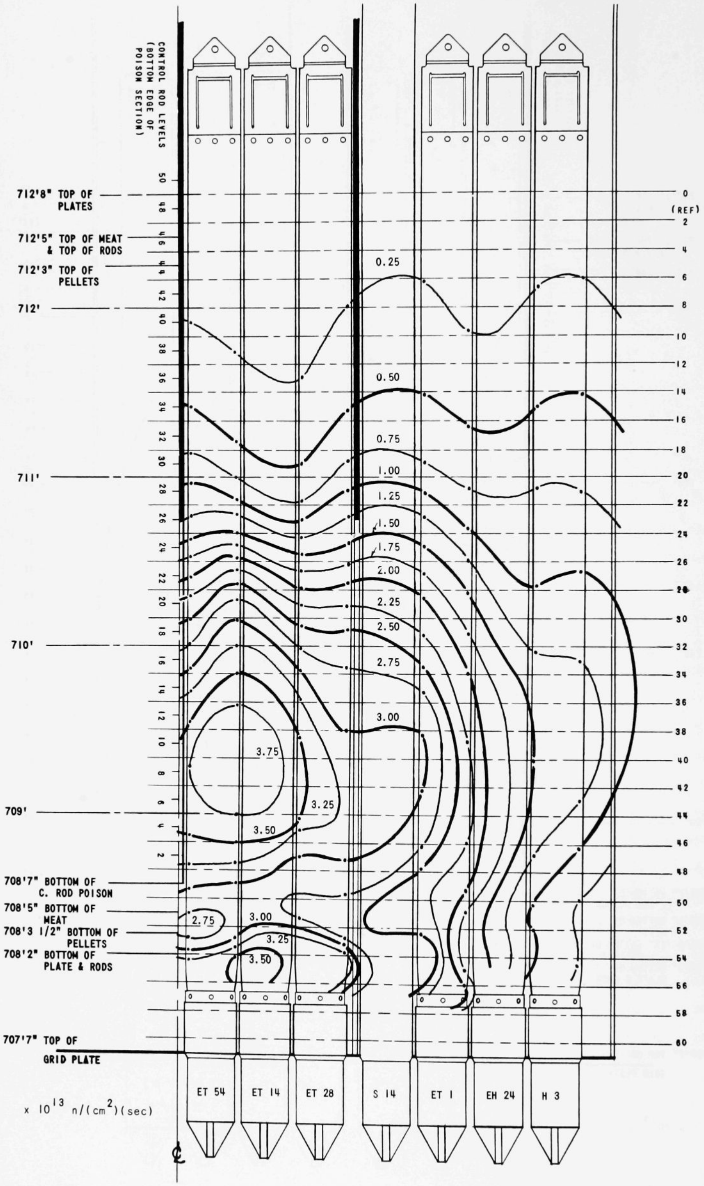

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Fig. 6. Thermal-neutron-flux Isogram Plot for Reactor Power of 41.2 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

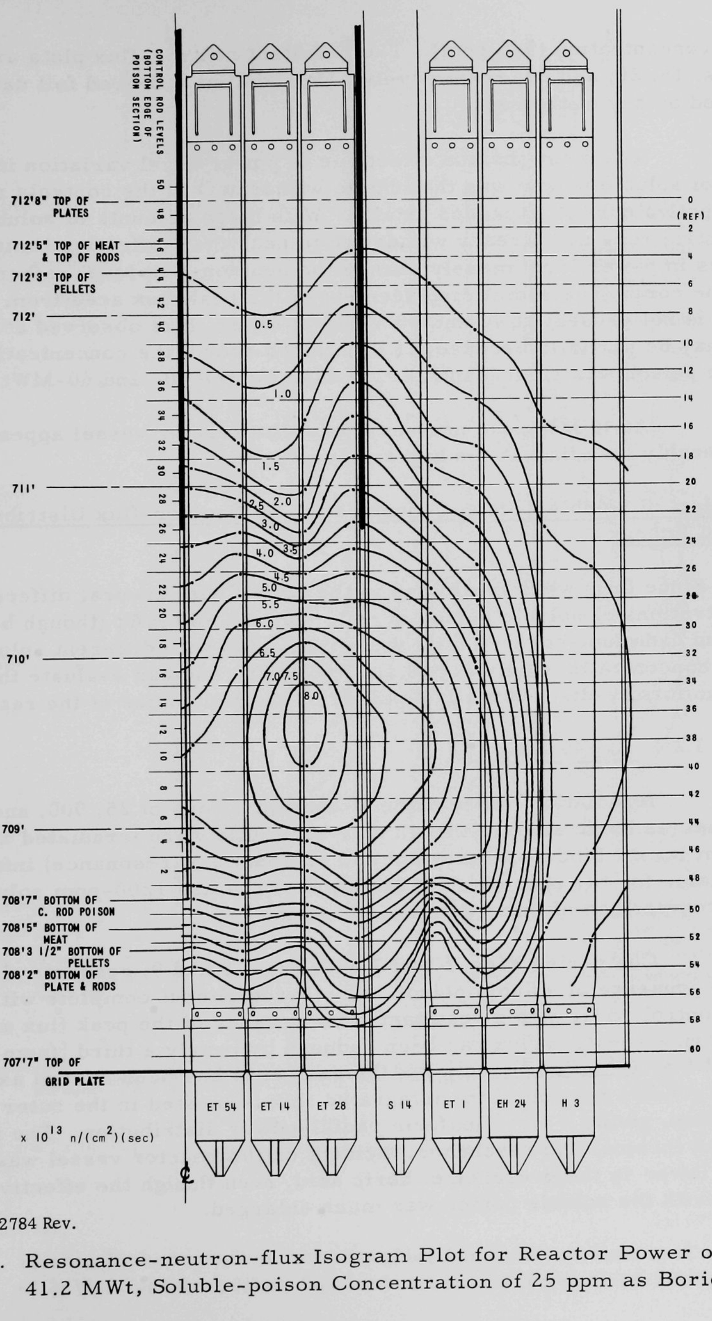

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Fig. 7. Resonance-neutron-flux Isogram Plot for Reactor Power of 41.2 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

lower concentration (540 ppm). The resultant neutron-flux plots are shown in Figs. 16, 20, and 24, respectively. No cadmium-covered foil data were obtained on any of the runs.

The most obvious effect due to power-level variation in the absence of soluble poison was that due to withdrawal of the controls rods; i.e., the effective core is expanded axially. With large amounts of soluble poison, the control rods are already withdrawn to near their effective limits so that changes in power level merely change the neutron-flux level rather uniformly over the core. The radial displacement of the peak flux area from the core center is not present at 40 and 60 MWt; however, it is observed at 80 MWt. This may be partially because, as mentioned above, the concentration of soluble poison was significantly lower than for the 40- and 60-MWt runs.

At 40 MWt, the neutron flux at the reactor vessel appears to be considerably less than at the higher power levels.

3.2 Effect of Soluble-poison Concentration on Neutron-flux Distribution and Energy

Since foils were irradiated in the EBWR with several different concentrations of soluble poison at ~40, ~60, and ~80 MWt (though both bare and cadmium-covered foils were irradiated with different soluble-poison concentrations only at ~40 and ~60 MWt), one can evaluate the effect of the uniformly-distributed 1/V poison on the neutronics of the reactor.

3.2.1 At ~40 MWt

Irradiations were made at concentrations of 25, 900, and 1200 ppm (as boric acid), although only bare foils were irradiated at the 900-ppm level. Since both thermal and epicadmium (resonance) information is available for the reactor at 40 MWt and at 25- and 1200-ppm soluble poison, a comparison of these data is interesting.

Comparing Figs. 6 and 7 with Figs. 8 and 9, respectively, shows that the presence of soluble poison has allowed almost complete withdrawal of the control rods, with a resultant shift upwards of the peak flux area. The peak thermal-neutron flux has been reduced by nearly a third [from 3.75×10^{13} to 2.6×10^{13} n/(cm^2)(sec)], and the peak area has been spread axially. A much greater portion of the integrated flux is located in the outer fuel assemblies, giving a more uniform radial-power distribution. The neutron flux, both thermal and resonance, incident on the reactor vessel was significantly lower in the presence of boric acid, even though the effective core volume with the soluble poison was much enlarged.

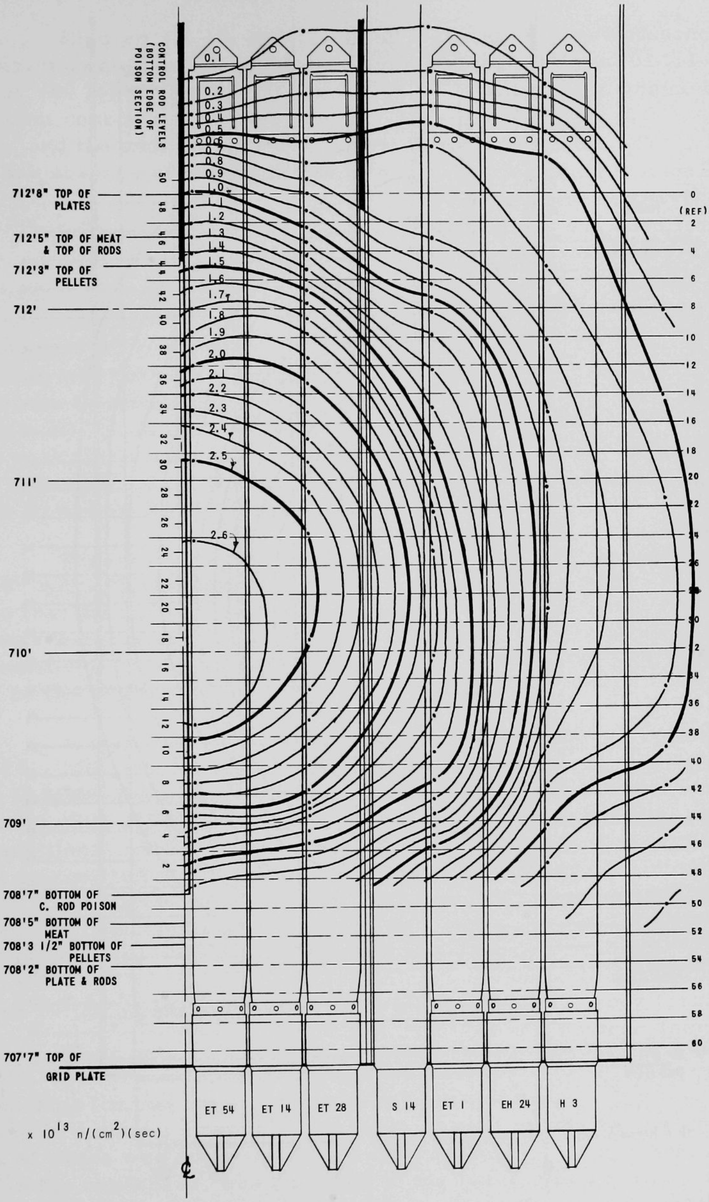

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Fig. 8. Thermal-neutron-flux Isogram Plot for Reactor Power of 42 MWt, Soluble-poison Concentration of 1200 ppm as Boric Acid

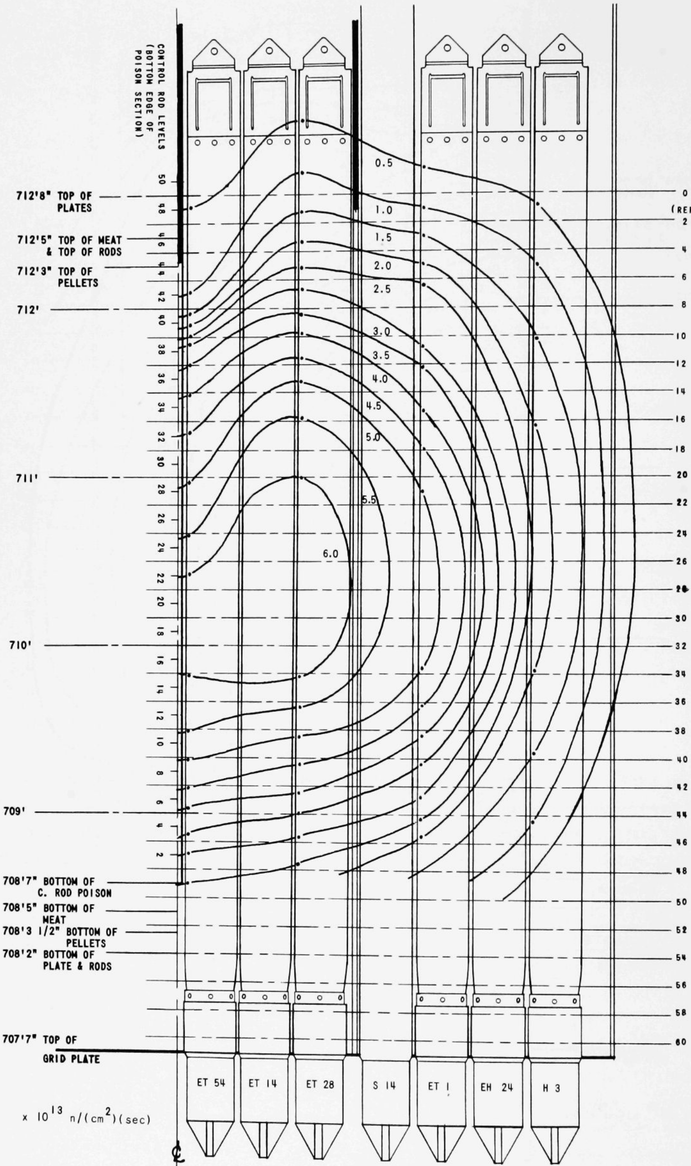

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Fig. 9. Resonance-neutron-flux Isogram Plot for Reactor Power of 42 MWt, Soluble-poison Concentration of 1200 ppm as Boric Acid

Figures 15, 16, and 17, which were constructed from bare-foil data only, indicate the intermediate concentration level of 900-ppm soluble poison at ~40 MWt. Though the peak flux is higher (as expected) than for a 1200-ppm concentration, the flux distribution through the core is quite uniform, and the neutron flux incident on the reactor vessel is much lower than in the absence of the soluble poison.

3.2.2 At ~60 MWt

At ~60 MWt, as at 40 MWt, one of the three sets of data does not include cadmium-covered foil information. The difference in soluble-poison concentration is much smaller for the other two sets (25 and 120 ppm), and the control rod configuration for the run with 120-ppm soluble poison was quite unusual due to rod oscillation studies being performed. Even so, the flux distribution, both thermal and resonance, was improved (see Figs. 10, 11, 12, and 13). The peak neutron flux was reduced by 20%, and the peak flux area was broadened and shifted upwards. Time did not permit a determination of the effect the lower position of the center control rod (No. 9) had on the distribution.

Figures 11 and 13 of the resonance flux, and particularly the 2.0×10^{13} n/(cm^2)(sec) isogram levels at the maximum radial positions, indicate that the addition of only ~100 ppm of boric acid to the coolant-moderator water provided some protection to the reactor vessel, in addition to its beneficial core-neutronics effects. This effect may have been enhanced by the position of the center control rod.

A comparison of the bare foil data presented in Figs. 18, 19, and 20 for 25-, 120-, and 925-ppm soluble poison, respectively, all at approximately 60 MWt, shows that much more of the advantage of soluble poison on the neutron-flux distribution was realized in the first ~100-ppm addition than in the additional ~800-ppm addition. This assumes that the position of the central control rod at 120 ppm did not greatly affect that flux distribution data. With the higher concentration, the peak flux is lowered and the area is enlarged and relocated higher in the core. The presence of soluble poison has definitely improved the neutron flux distribution.

3.2.3 At 72 to 80 MWt

Four sets of data were obtained during this high-power operation of EBWR; however, personnel access limitation into the reactor containment building limited the irradiations to bare foils only. The reactor was operating in a unique manner(11) at these powers in that an unusually large amount of water was entrained in the effluent steam. This water, after being cooled in the condenser, was returned to the reactor in a manner similar to that in dual-cycle boiling reactor systems. Since the amount of carry-over was a direct function of the water level in the reactor, operation at any given power could be accomplished with a variety of control rod positions, dependent almost entirely on the subcooling resulting from the return of large quantities of the cold water from the condenser.

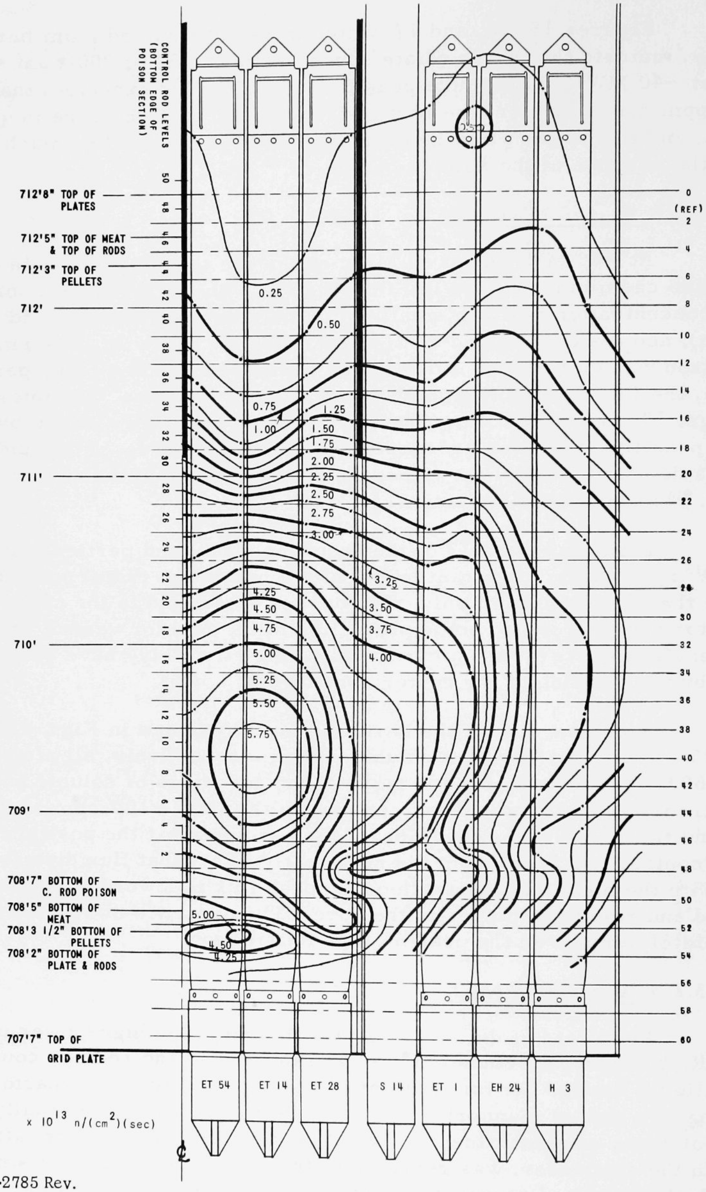

Fig. 10. Thermal-neutron-flux Isogram Plot for Reactor Power of 62 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

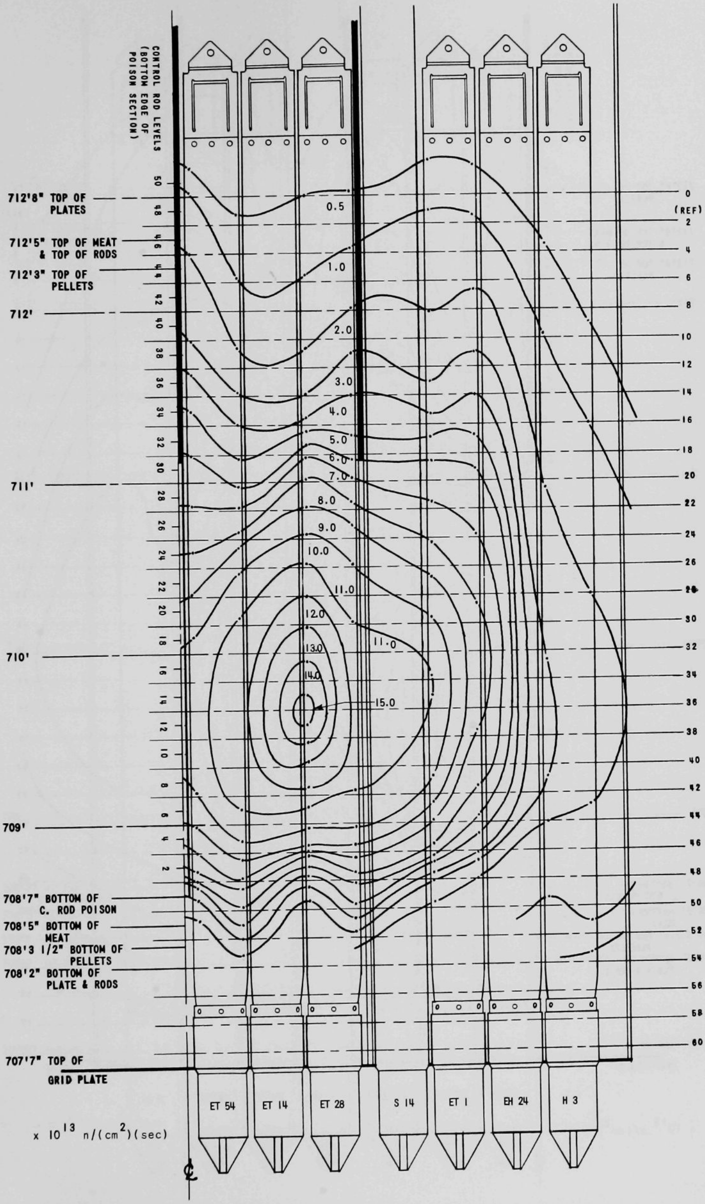

Fig. 11. Resonance-neutron-flux Isogram Plot for Reactor Power of 62 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

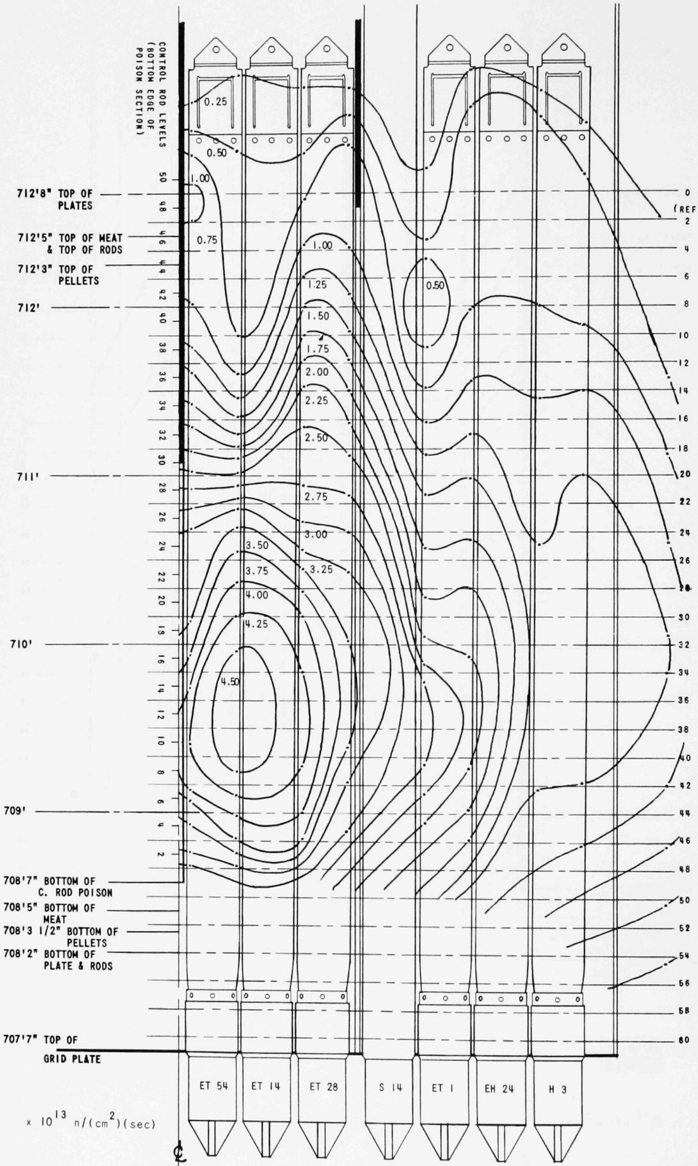

Fig. 12. Thermal-neutron-flux Isogram Plot for Reactor Power of 58 MWt, Soluble-poison Concentration of 120 ppm as Boric Acid

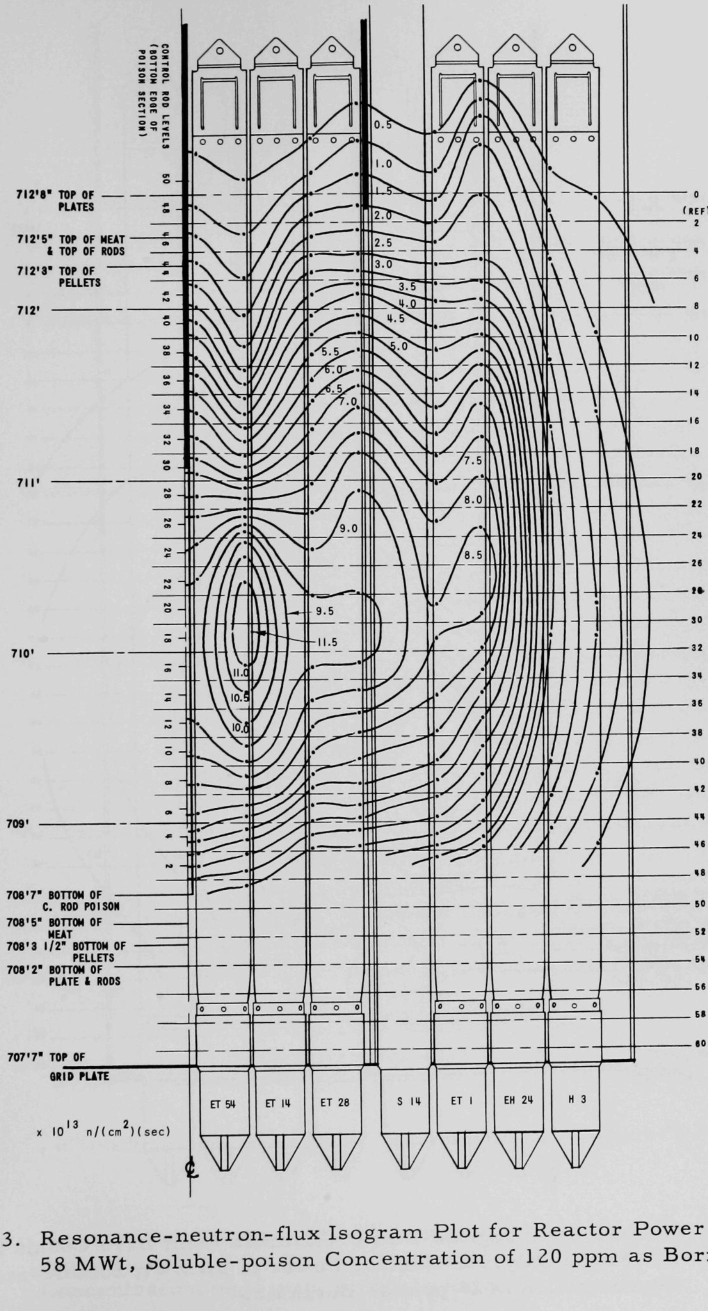

Fig. 13. Resonance-neutron-flux Isogram Plot for Reactor Power of 58 MWt, Soluble-poison Concentration of 120 ppm as Boric Acid

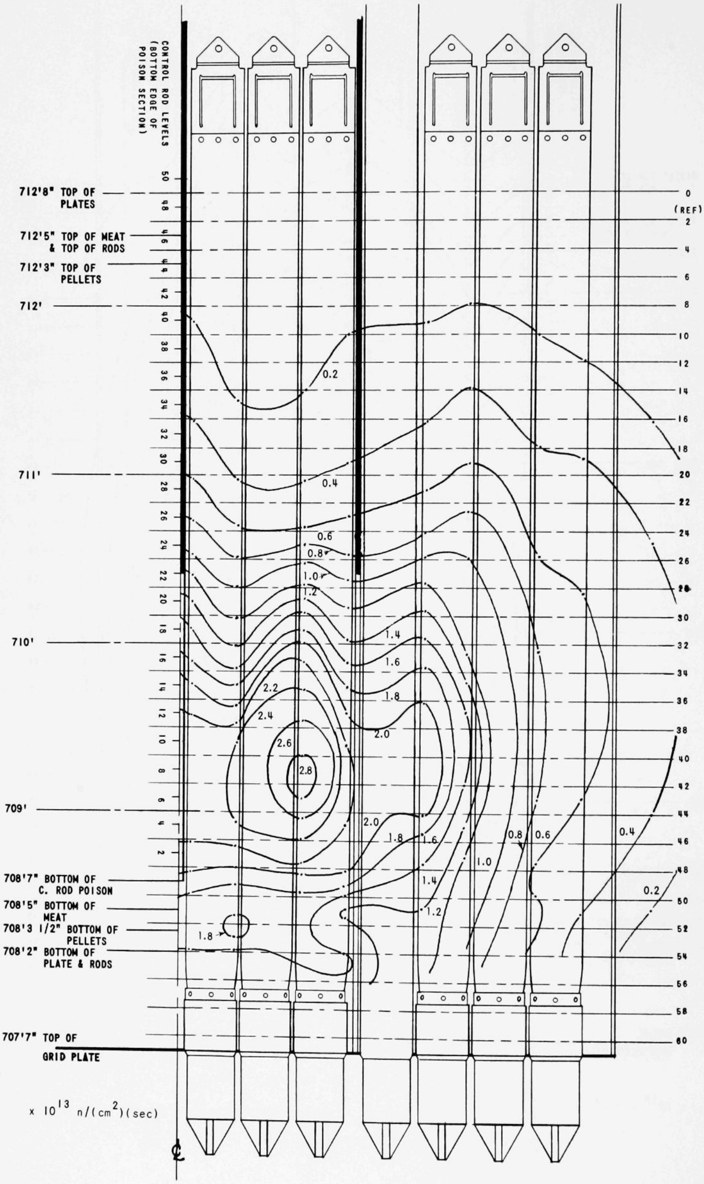

Fig. 14. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 21 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

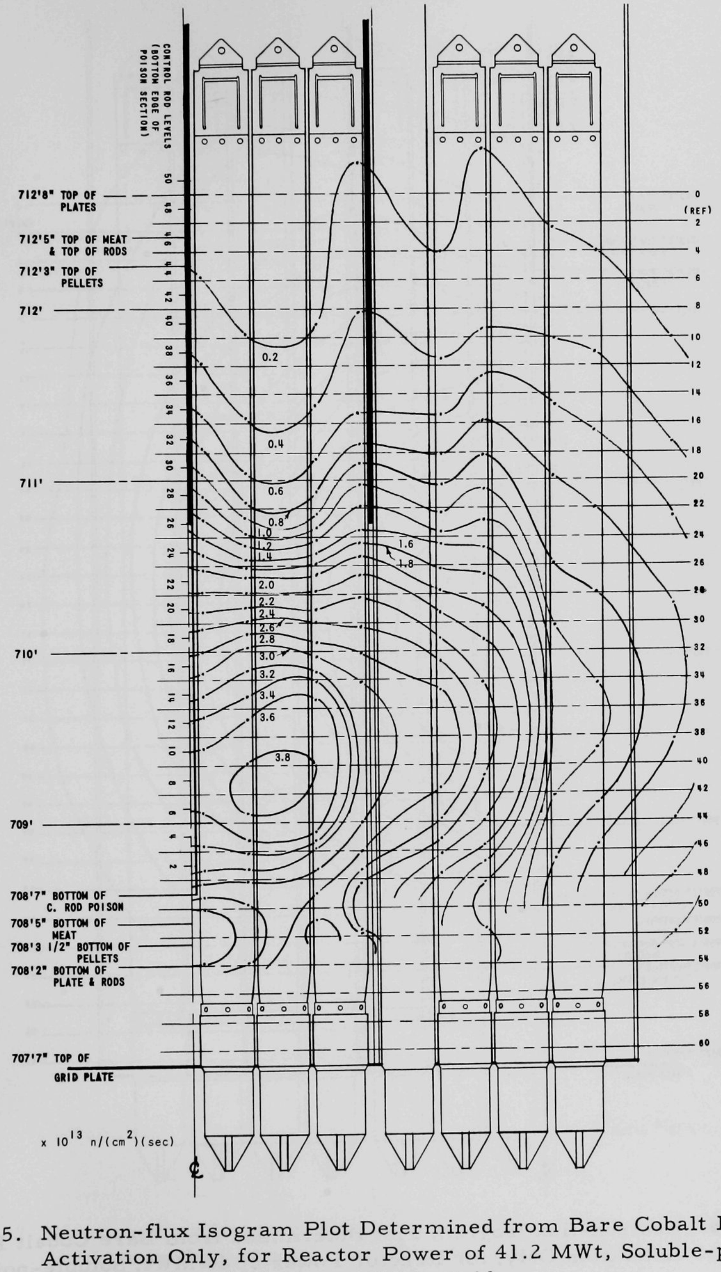

Fig. 15. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 41.2 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

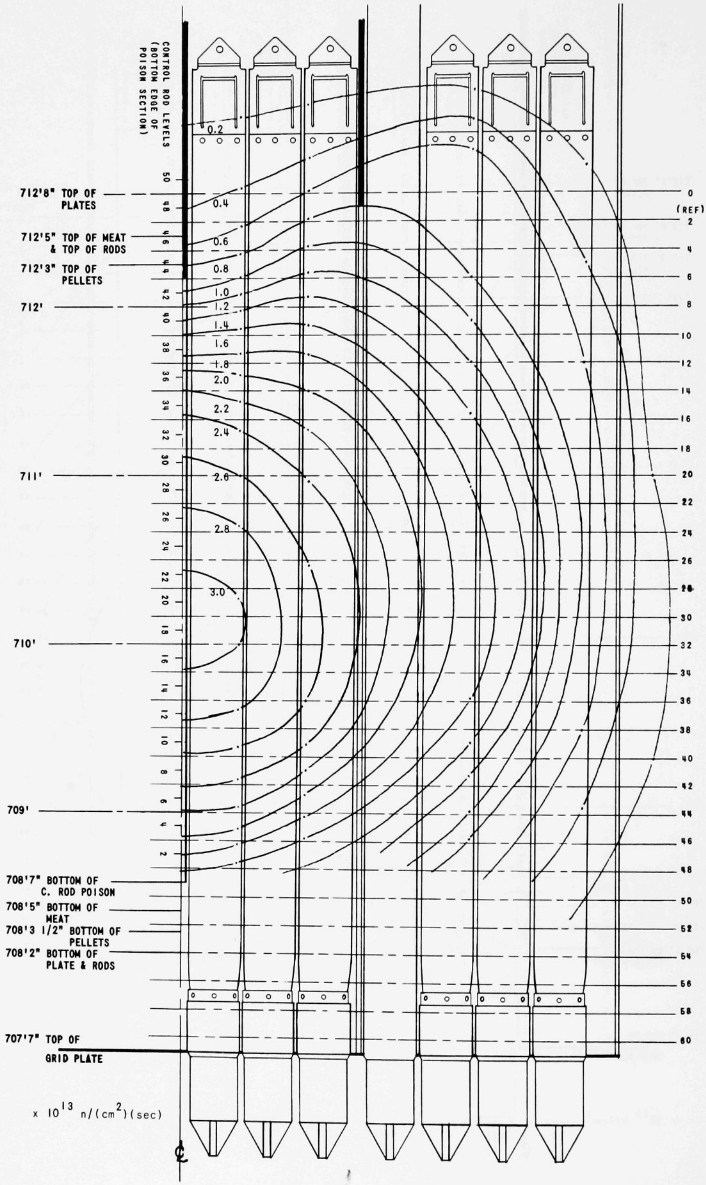

Fig. 16. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 40 MWt, Soluble-poison Concentration of 900 ppm as Boric Acid

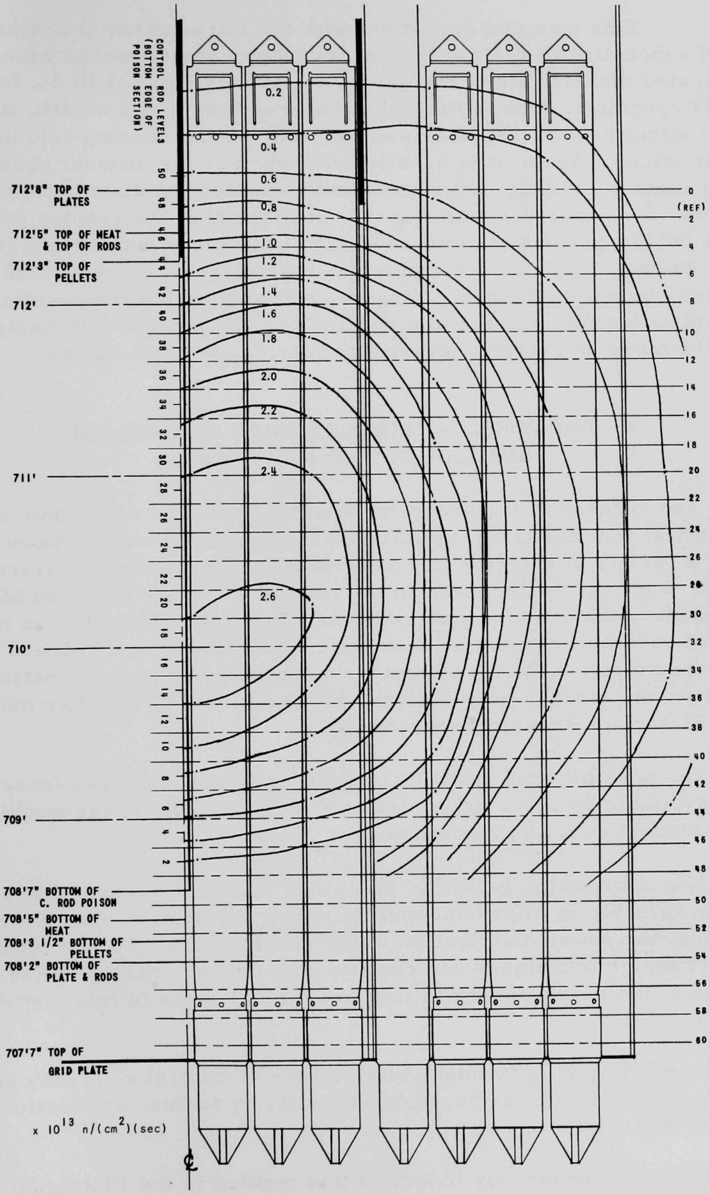

Fig. 17. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 42 MWt, Soluble-poison Concentration of 1200 ppm as Boric Acid

This complex operation, with the introduction of another variable (that of subcooling due to carry-over as a function of reactor water level) complicated the analysis of the data presented in Figs. 21 to 24, for 72- to 80-MWt operation. One is limited to observations of the modification of the overall effective core shape as a consequence of increasing soluble-poison concentrations. Again, it is questionable whether the unusual position of the central control rod (Fig. 23) significantly affected the distribution of the neutron flux. A comparison with Fig. 22, in which both the reactor power and soluble poison concentration were similar, indicates that the effective core in Fig. 23 has a much larger and more uniform radius. How much of this effect may be due to the subcooling is questionable, but the possibility of power-distribution tailoring in a reactor core by control rod manipulation should be more extensively investigated for future applications.

4. PROPOSED FUTURE STUDIES IN EBWR OR SIMILAR POWER REACTORS

The success of the program reported above, in which only cobalt foil material was available, indicates that an extension of the work should include a variety of detector foil materials selected to best characterize the neutron energy encountered in the reactor core. Carver and Morgan[2] selected just such a list of materials (see Table II). They did not have the benefit of cadmium covers, so that use of those materials with and without covers should give a wealth of neutron-energy spectrum information. Such a selection has already been obtained for use in the EBWR after modication for the Plutonium Recycle Experiment.

The possibility of using fissionable isotopes for power-reactor studies is also available by this method and may be explored. These would have particular interest with a plutonium core.

The information gained in this study makes it obvious that a soluble poison is valuable in improving and flattening the neutron-flux distribution and, hence, the power distribution in the reactor core. Future studies by flux-distribution techniques and coupled with burnup analyses after prolonged operation would be necessary to confirm the full value of this control technique.

Power tailoring through judicious use of control rods may give better fuel economy, and this can be explored easily by further application and extension of this study.

Plans are under way to utilize this method in the Plutonium Recycle Experiment (modified EBWR). Computer analysis of the data is definitely indicated for the large number of detector foils that will be used.

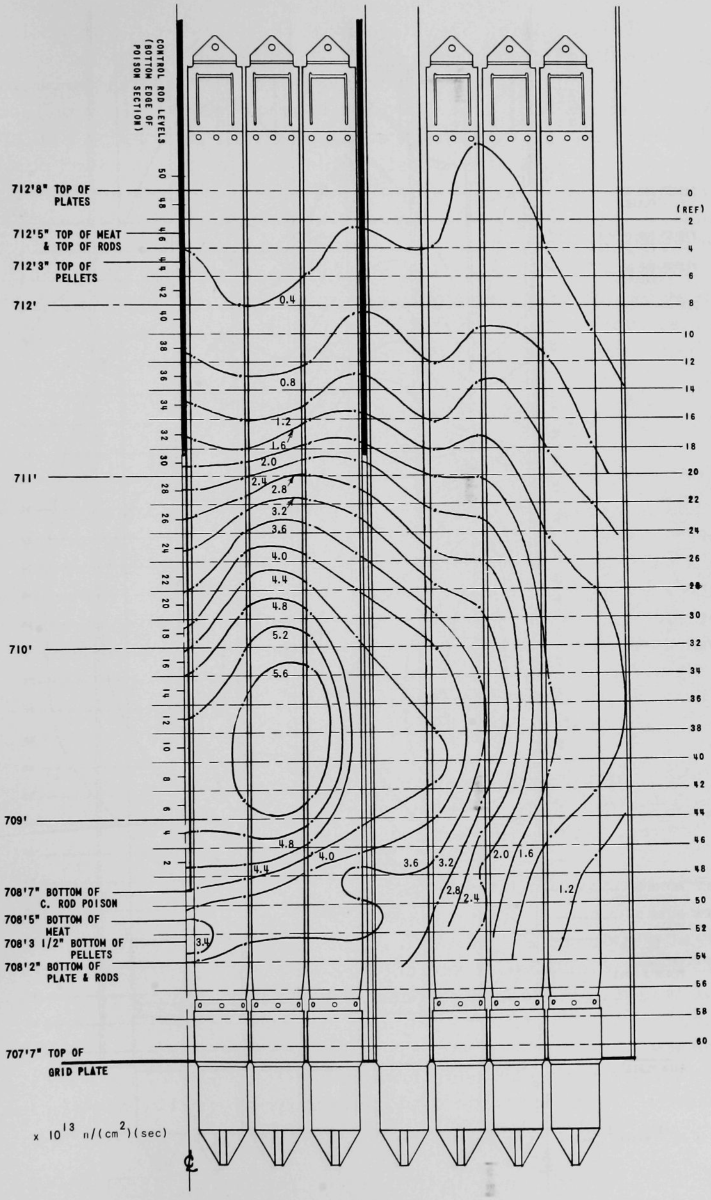

Fig. 18. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 62 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

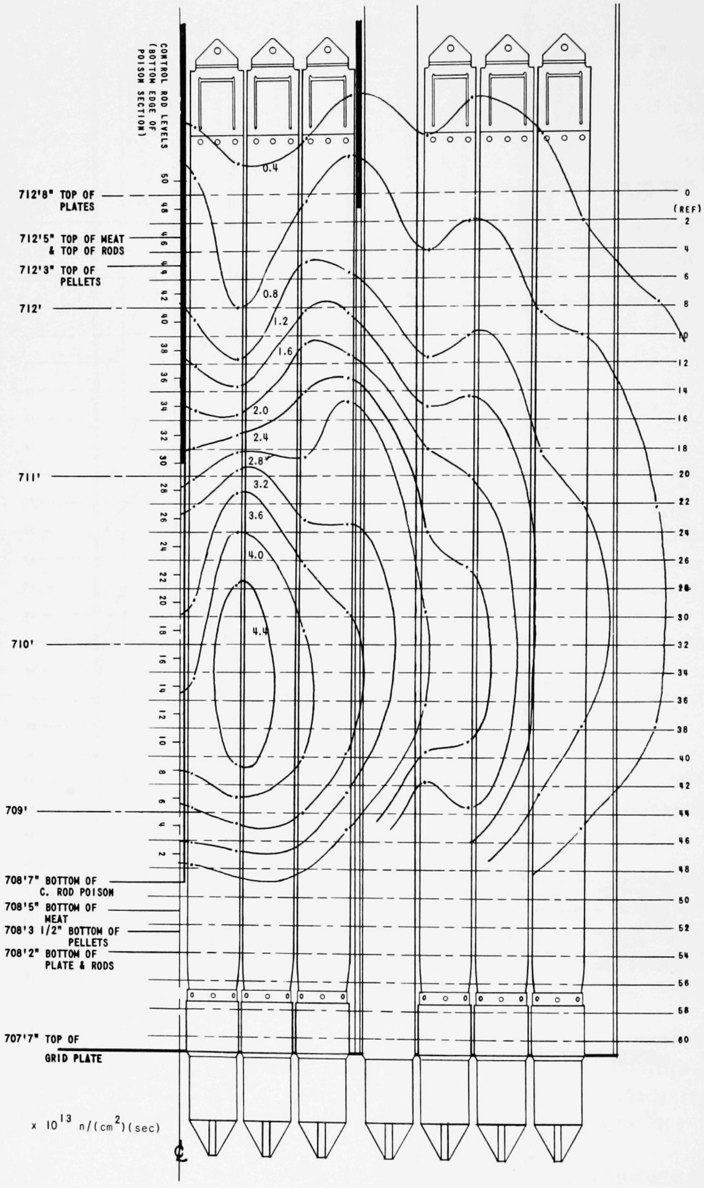

Fig. 19. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 58 MWt, Soluble-poison Concentration of 120 ppm as Boric Acid

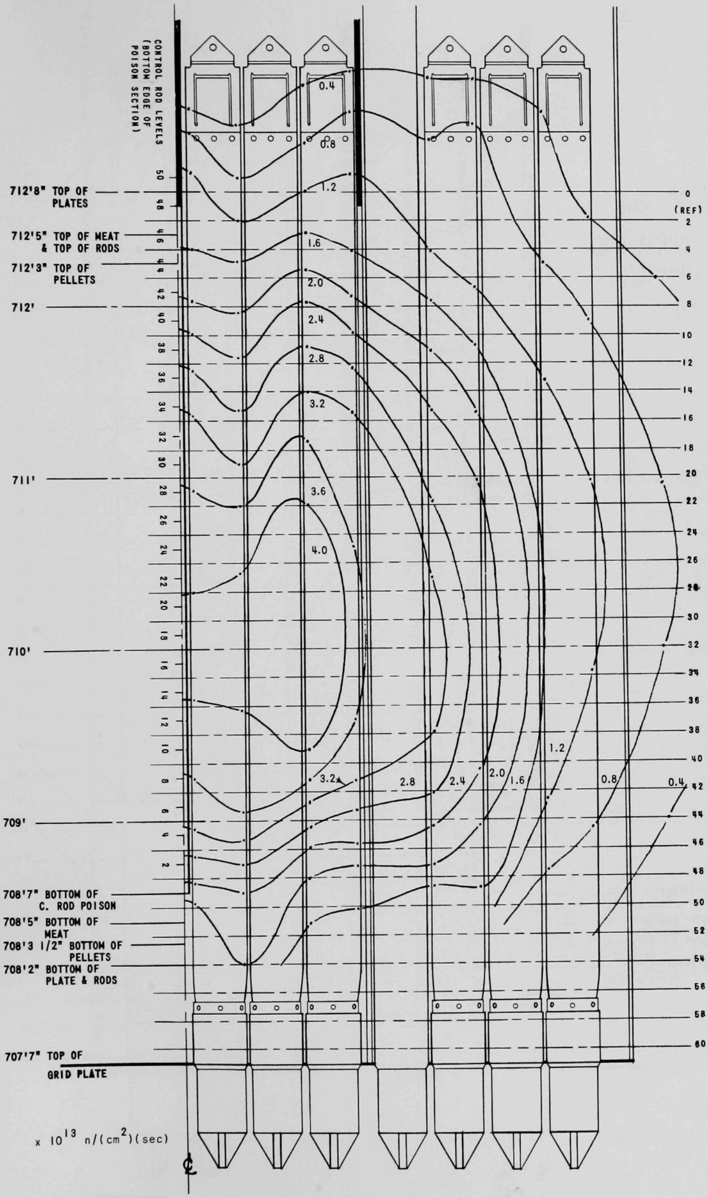

Fig. 20. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 60 MWt, Soluble-poison Concentration of 925 ppm as Boric Acid

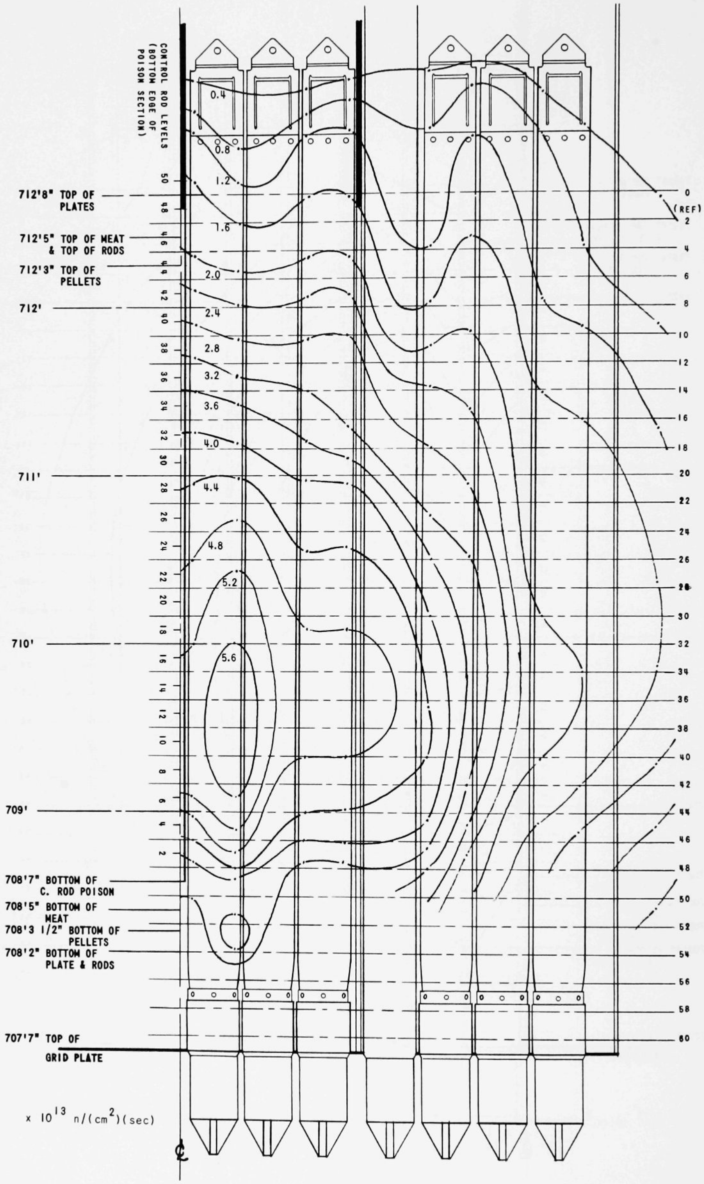

Fig. 21. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 78-80 MWt, Soluble-poison Concentration of 25 ppm as Boric Acid

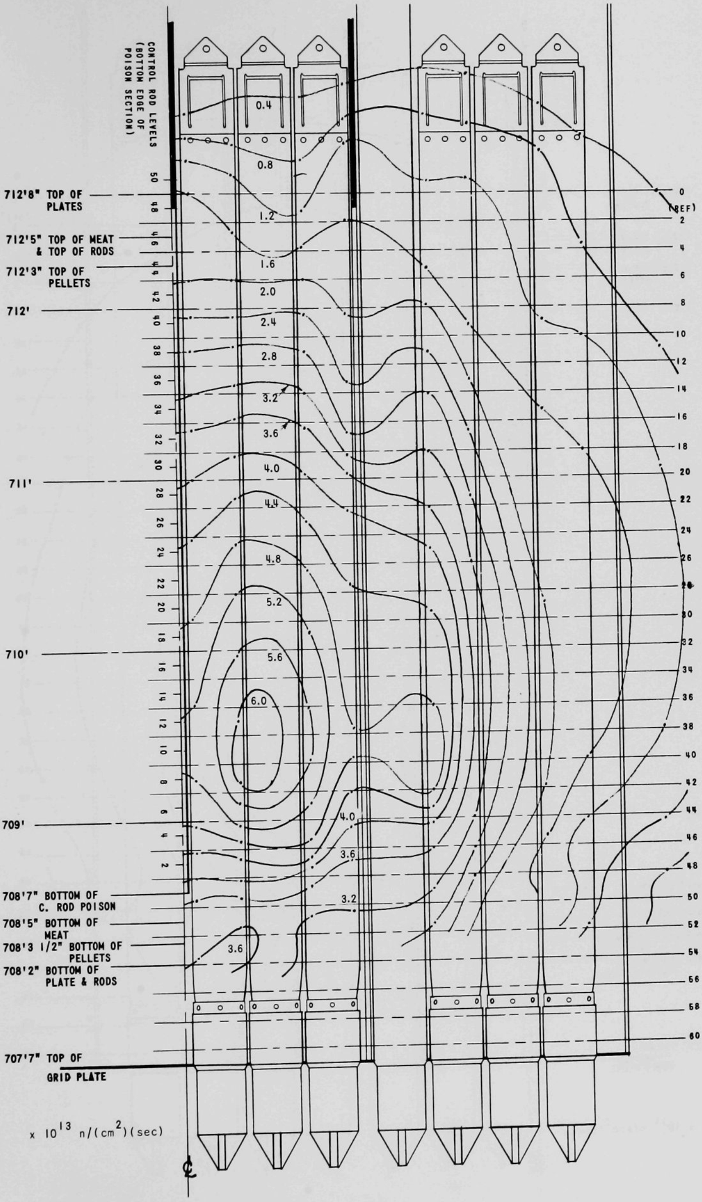

Fig. 22. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 72 MWt, Soluble-poison Concentration of 225 ppm as Boric Acid

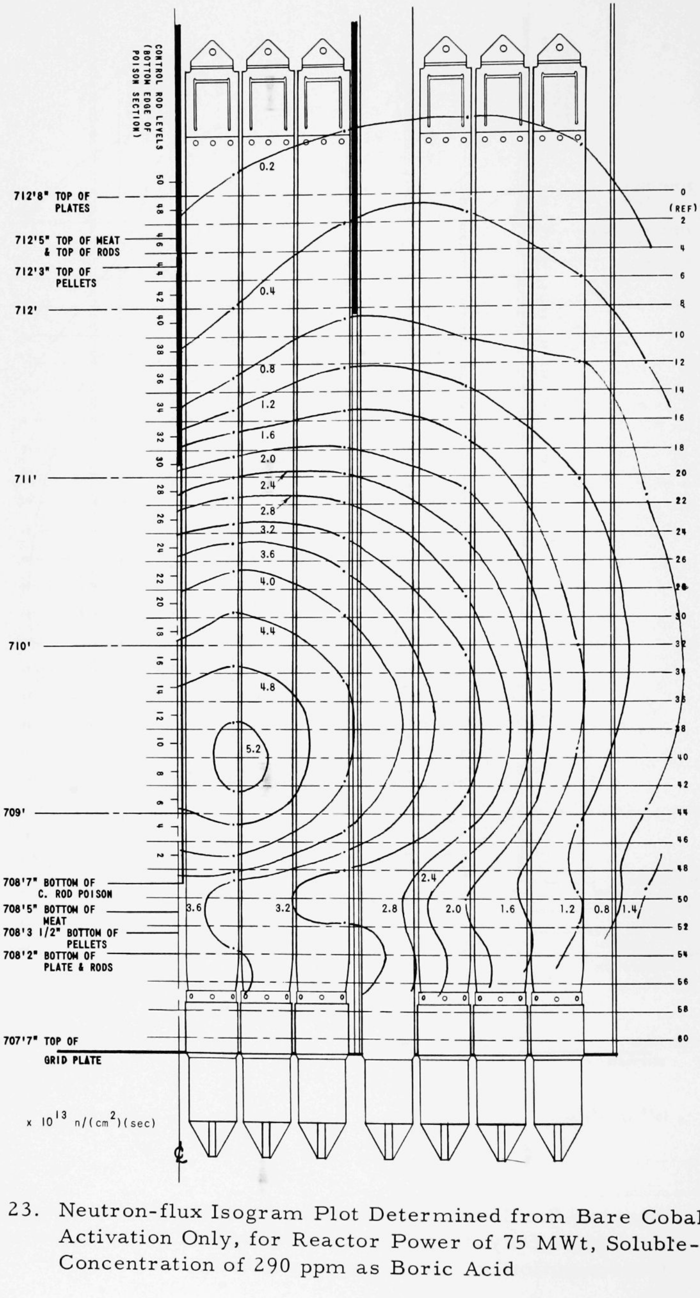

Fig. 23. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 75 MWt, Soluble-poison Concentration of 290 ppm as Boric Acid

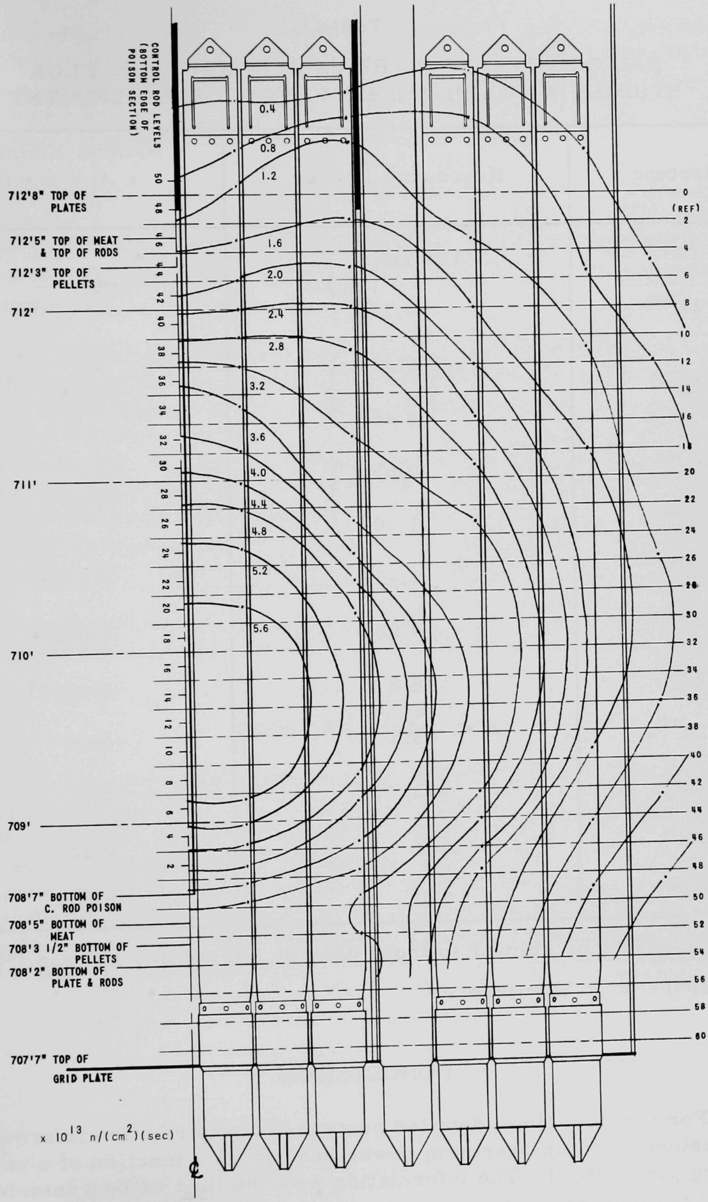

Fig. 24. Neutron-flux Isogram Plot Determined from Bare Cobalt Foil Activation Only, for Reactor Power of 80 MWt, Soluble-poison Concentration of 540 ppm as Boric Acid

Table II

RADIOACTIVANTS TO BE USED IN NEUTRON-FLUX STUDIES IN THE PLUTONIUM RECYCLE EXPERIMENT

Isotope	Resonance Energy	Natural Element in Aluminum (w/o)
Lu^{175}	1/V Only	~6*
Lu^{176}	0.143	
Eu^{151}	0.321 0.461	~0.2*
Ir^{191}	0.654	~0.25*
Ir^{193}	1.303	
In^{115}	1.457	0.033*
Au^{197}	4.906	0.056*
W^{186}	18.8	~0.065**
La^{139}	73.5	~0.6*
Co^{59}	123	1.01
Mn^{55}	337	0.82
Cu^{63}	580	0.47*

*Concentrations similar to those used by Carver and Morgan.(2)

**Suspension in aluminum.*

CONCLUSIONS

For the first time, detailed neutron-flux distribution information has been obtained from an operating power reactor as a function of a variety of operating parameters. The information was obtained without interfering with normal reactor operation.

The effects of power changes and soluble-poison concentration have been evaluated, with the obvious conclusion that the neutron-flux distribution and, hence, power distribution in the reactor core are greatly improved in the presence of maximum quantities of soluble poison, i.e., a sufficient quantity to allow nearly complete withdrawal of the control rods.

By reducing neutron leakage from the core through the use of soluble poison, the neutron flux impinging on the reactor vessel (and, it is assumed, the consequent radiation damage) is reduced. Likewise, the peak of thermal reflux neutrons at the bottom of the core (in the vicinity of the support plate) is also reduced.

One of the most obvious conclusions is that more work is needed to extend the knowledge of operating parameter effects on the core power distribution. Such studies should be under the control of the experimenter (contrary to the present case in which the compressed operation schedule of the reactor facility during the preparation and approach to high-power operation was the controlling factor over all the experimentalists involved in the program) to the extent that additional irradiation locations should be available, and the operating parameters should be adjusted for irradiations to maximize the effect under study while reducing interfering effects.

In spite of the limitations encountered by the present study, much useful information was obtained, justifying the effort expended.

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